Considering Holding Cost in Optimal Core Acquisition and Remanufacturing Policy under Deterministic Process Times

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Abstract

This paper considers holding cost in core acquisition policy. High variability in quality of returned products complicates decision making on the quantity of products to acquire and remanufacture each period. On the other hand, inventory costs are considered only in multi-period or inventory control models, while WIP costs (charged due to waiting times for products in the intermediate storage areas) are ignored. In this research work, holding cost for finished and unfinished products is considered with two different approaches in two MINLP models, under the assumption of deterministic process times. It is found that, although different products go through different production lines, reducing the time of the process with the lowest production rate has the largest impact on the total holding cost.

Keywords
Remanufacturing, WIP cost, MINLP model, Quality, Categorizing

1. Introduction

Remanufacturing has been the focus of many researches and studies. Legislations, potential profit and environmental issues are among the most important driving forces to remanufacture (Nenes and Nikolaidis, 2012). In this context, there is a myriad of papers in the literature, making different assumptions and taking several considerations into account. Ferguson et al. (2009) considered continuous quality levels for the returned products and did categorizing by a multi-period model under deterministic quality conditions of the returned products. Denizel et al. (2010) continued this work by considering uncertainty and quality conditions of the returned products and applying stochastic programming. Galbreth and Blackburn (2010) found a closed-form solution for optimal quantity of acquirable cores under linear remanufacturing cost and uniform quality condition level for returns. Teunter and Flapper (2011) considered discrete quality levels for returns and searched for optimal acquisition policy. They confirmed the impact of quality uncertainty of the returned products on the optimal number of acquired products. Cai et al. (2013) presented a stochastic dynamic mathematical modeling considering two levels for quality conditions. Jin et al. (2013) also considered two quality levels. However, they assumed that the products with high quality levels can be substituted by low quality level products to satisfy demands. Quality level of the returned products may follow continuous distributions such as Beta (Ferguson et al., 2009) or Uniform (Galbreth and Blackburn, 2010), or discrete distributions such as Multinomial (Teunter and Flapper, 2011).

Inventory cost is considered in multi-period mathematical models. In papers considering holding cost, products which are acquired but not remanufactured in a period charge holding costs for one period (Teunter and Flapper, 2011; Mahapatra et al. 2012). In addition, some studies have considered infinite planning horizon for inventory control and presented the optimal inventory control policy (Li et al., 2013). In the first case for multi-period models, if the length of period is large, say 1 year, holding cost for a huge number of products which are acquired and remanufactured in the same period is ignored. That means no holding cost for a period in which all of the acquired products are completely remanufactured, which is not true. On the other hand, in these papers the planning horizon is not short, thus acquisition decisions are deemed to be tactical rather than operational. Besides, with rapid changes in technology, many products are progressing in terms of features and design. Hence, products should be remanufactured and sent back to the market as soon as possible to tackle with the risk of obsolescence. Therefore, multi-period models are not applicable for many high-tech goods. In this research study, holding cost for all of the products acquired and remanufactured is investigated in details.

One of the most important processes in remanufacturing is categorizing. Categorizing is proved to reduce WIP, simplify production planning and control and cause considerable costs savings (Aras et al., 2004). After the returned products are divided into categories, they should undergo specific remanufacturing processes to be recovered. If there is a high quantity of products in a certain category with high required processing time, products have to be held in buffers and intermediate storage areas for a long period of time; and that is the situation at which WIP cost becomes significant. Holding cost is a considerable proportion of operational costs for a firm. WIP means:

- The investment which is not converted into money yet
- Holding products in warehouse and buffers
- Potential risk of obsolescence

Even the finished but not yet sold products have the same meaning for the company. Figure 1 below depicts the flow of materials in a remanufacturing process.

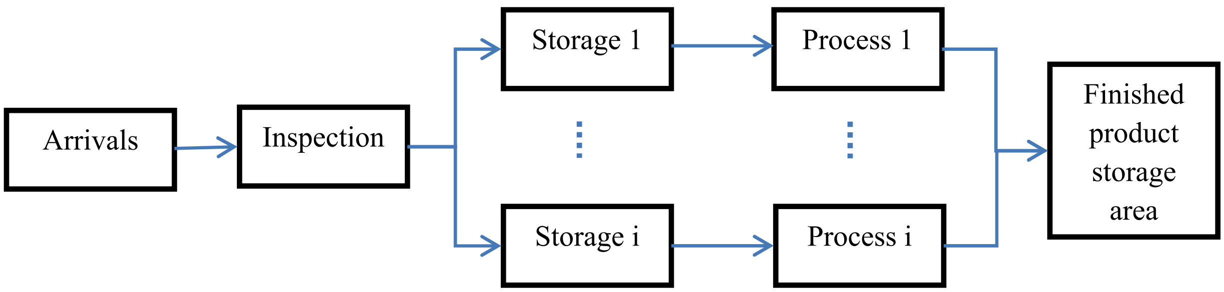

Figure 1: Structure of the remanufacturing process

Products are received and stored in “Arrival” as the primary storage area. Then they should be inspected one by one. According to the quality conditions of each item, then they are directed to appropriate work stations for remanufacturing processes. When the items are remanufactured successfully, they should be stored in the finished product storage area and wait for being shipped to the customers.

In this research, we will calculate total holding cost on the basis of the duration at which the unfinished/finished products spend in the storage areas. To the best of our knowledge, there is no paper in the literature considering single-period holding cost (storage cost charged for holding unfinished and/or finished products in final/intermediate storage areas) in operational point of view with the addressed approach.

In this paper, holding cost is incorporated in existing mathematical models in the literature with discrete and deterministic quality levels for the returned products. Two MINLP models are created to address the following two holding cost cases:

- All the products remanufactured in a category would be totally shipped to customer (s). In this case, makespan is targeted.
- Each product would be shipped to customer after finishing processing. In this case, unit completion time is considered in calculating holding cost.

In the first case, the money invested in buying back and remanufacturing the returned products would result in revenue after the last product in that category is remanufactured. Each product would be sold immediately after being completed in the second case.

2. Problem Definition and Traditional Categorizing Model

In this section, the assumptions are specified and a MIP model for categorizing the returned products on the basis of addressed assumptions is presented. The model is a simple profit maximization model subjected to demand satisfaction.

A batch of returned products is received, inspected, sorted and then categorized to different groups. The proportion of products belonging to each group follows multinomial distribution as in Teunter and Flapper (2011). These proportions are known in advance, thus, quality of the returned products is deterministic in this research. Each category has its unique remanufacturing cost and selling price for the remanufactured products. In Guide and Wassenhove (2003), it is implied that sometimes the remanufacturing company may choose to remanufacture less and sell the remanufactured products with lower prices and lower level of quality. Quality-dependent selling prices are emphasized in Guide and Wassenhove (2003) and considered in Pokharel and Liang (2012) and in Das and Chowdhury (2012). *Thus, it is assumed that although remanufacturing costs and selling prices for the products within each category are the same (products are identical in each category), for different quality-based categories remanufacturing costs and selling prices are different*. Since different markets would be targeted for different quality levels of remanufactured products and different prices, *different demands are considered in this model for different quality categories. The goal is to find the optimal number of received products to maximize total profit.*

The following notation is used for presenting the model.
A: Total number of acquirable products
A^*: Optimal number of acquired products
I: Set of product categories
p_i: Proportion of products which can be placed in category $i \in I$. In other words, the probability that a product may be placed in category $i \in I$
D_i: Demand for the remanufactured products of category $i \in I$
c_i: Remanufacturing cost for the products of category $i \in I$
pr_i: Selling price (recoverable value) for the products of category $i \in I$
ε: The discount considered for the remanufactured products if it exceeds demand.

The mathematical model:

Objective Function: Maximize $$\sum_{i \in I}[A^* p_i(pr_i - c_i) - pr_i(A^* p_i - D_i)\varepsilon] \quad (1)$$

Subject to:

$$A \geq A^* \quad (2)$$

$$A^* p_i \geq D_i \quad (3)$$

Equation (1) is the objective function that maximizes total profit. The first term of the objective function is to maximize profit while the second term put penalty for the extra products remanufactured. This can also be considered as discounts or incentives the remanufacturer puts to create future demand or increase the quantity of sale. Quantity discount is approved to have positive effects on supply chain coordination (Li and Liu, 2006). Constraint (2) makes sure the optimal number of acquired products does not exceed the total number of acquirable products. Demand satisfaction is stipulated by constraint (3). Section 3 below describes the effect of WIP cost.

3. Incorporating WIP cost into traditional categorizing models

To present the new model, a few more parameters are required to be defined.
λ: Inspection rate
μ_i: Processing rate for the remanufacturing process related to category $i \in I$
α: The unit holding cost for finished or unfinished products for a period of time
TWT_i: Total waiting time for the products placed in category $i \in I$
AI: The time at which an item arrives to the inspection center
AS: The time at which an inspected items arrives to the storage area
WI: The duration an item has to wait to be inspected
WS: The duration of time an item has to wait in the storage area to be remanufactured.

Usually, when a returned product is received, it should undergo a thorough inspection. This inspection procedure is the same for many of the products. In addition, in some research studies such as Tagaras and Zikopoulos (2008), sorting cost is identical for all of the unsorted returned products. Hence, it can be logically assumed that, the same equipment and time are employed to inspect all of the products. Consequently, inspection rate is the same for all of the returned products, disregarding the quality level. Figure 2 depicts such a remanufacturing line. This line is one branch of the manufacturing line depicted in Figure 1.

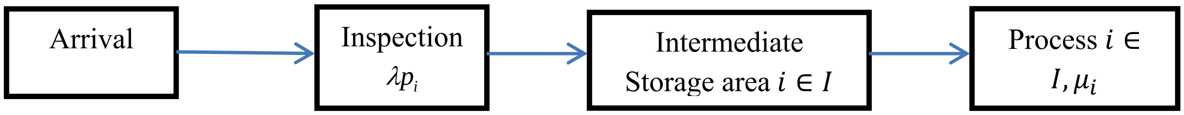

Figure 2: Material flow chart for remanufacturing line

It is also assumed that inspection rate is much higher than remanufacturing rate, so a queue is created behind the process in the intermediate storage area. A batch of returned products arrives at inspection. Regarding this fact, the waiting times for the products can be obtained according to Table 1. The first item in the inspection center waits no time to be inspected. Then, it undergoes inspection time equal to $1/\lambda p_i$. After being inspected, it is sent immediately to the storage area. So, considering time zero for items' arrival to the inspection center, the arrival time to the storage area is $1/\lambda p_i$, which is the summation of waiting time to be inspected and the inspection time. Since this is the first item to remanufacture, there is no other item in the storage area. Therefore, there would be no waiting time in the storage area for this item and it is sent immediately to be remanufactured. Remanufacturing time is $1/\mu_i$. Completion time can be obtained by adding remanufacturing time, waiting time in the storage area and arrival time to the storage area, which is $1/\mu_i + 1/\lambda p_i$ for the first item. The procedure to find out the completion times for the next items is exactly the same. However, waiting times for inspection and in the storage area must be noticed carefully. The second item arrives to the inspection center at time zero. While the first item is being inspected, the second item has to wait in the inspection center. Therefore, the waiting time for the second product in the inspection center is equal to the inspection time of the previous item in the inspection center ($1/\lambda p_i$). Then it has to undergo inspection before being sent to the storage area. Thus, the time it reaches storage area (AS) is the summation of waiting tie in the inspection center and inspection time ($2/\lambda p_i$). Since the remanufacturing time is greater than inspection time, the second item has to wait in the storage area for the first item to be remanufactured. In the other words, the second item can be remanufactured when the completion time of the first item is reached. Therefore, the waiting time for the second item in the storage area (WS) can be calculated by subtracting its arrival time to the storage area (AS) from the first item's completion time ($1/\mu_i - 1/\lambda p_i$). Finally, the second item's completion time is the summation of its waiting time in the storage area (WS), arrival time to the storage area (AS) and the remanufacturing time.

Table 1: Waiting times and processing times for the material flow chart under study

Item #	1	2	3	4
AI	0	0	0	0
WI	0	$1/\lambda p_i$	$2/\lambda p_i$	$3/\lambda p_i$
Inspection time	$1/\lambda p_i$	$1/\lambda p_i$	$1/\lambda p_i$	$1/\lambda p_i$
AS	$1/\lambda p_i$	$2/\lambda p_i$	$3/\lambda p_i$	$4/\lambda p_i$
WS	0	$1/\mu_i - 1/\lambda p_i$	$2/\mu_i - 2/\lambda p_i$	$3/\mu_i - 3/\lambda p_i$
Remanufacturing time	$1/\mu_i$	$1/\mu_i$	$1/\mu_i$	$1/\mu_i$
Completion time	$1/\mu_i + 1/\lambda p_i$	$2/\mu_i + 1/\lambda p_i$	$3/\mu_i + 1/\lambda p_i$	$4/\mu_i + 1/\lambda p_i$

From Table 1, the total waiting time for the j^{th} product in the i^{th} category can be calculated as follows:

$$WT_{ij} = \frac{1}{\lambda p_i} + \frac{j}{\mu_i} \tag{4}$$

It is assumed that the remanufacturing facility under consideration operates one shift per day. It is worth noting that many remanufacturing companies do manufacturing as well (Hybrid (re) manufacturing systems). Thus, the time devoted to remanufacturing is usually less than that the manufacturing time. Hence, the total required working time to remanufacture all of the items is not continuous; there are interruptions due to manufacturing times or off-shifts.

3.1 WIP cost with makespan

If the facility does shipping after all of the products in a category are remanufactured, waiting time of each unit is equal to the waiting time of the last unit. Considering hour (hr) as the time unit and 8 hours for a working shift, the total number of required shifts (R_i) to finish remanufacturing of the products placed in category $i \in I$ can be calculated as follows:

$$R_i = \left\lceil \frac{\frac{A^* p_i}{\mu_i} + \frac{1}{\lambda p_i}}{8} \right\rceil \quad (5)$$

The nominator is the total time required to remanufacture all of the products placed in category $i \in I$. Dividing this required time by the number of available hours for one day is the number of required working days to complete remanufacturing of all items in category $i \in I$. Since one shift is assumed per day, we replaced the term "shifts" by "day" in the rest of this paper. Hence, the total waiting time for the products placed in category $i \in I$ can be calculated by equation (6):

$$TWT_i = 16(R_i - 1) + \frac{A^* p_i}{\mu_i} + \frac{1}{\lambda p_i} \quad (6)$$

To consider holding cost with the addressed assumptions, the objective function (1) should be revised as follows:

$$Maximize \;\; \sum_{i \in I} \left(A^* p_i (pr_i - c_i) - pr_i (A^* p_i - D_i)\varepsilon + A^* \alpha \left(16 \left(\left\lceil \frac{\frac{A^* p_i}{\mu_i} + \frac{1}{\lambda p_i}}{8} \right\rceil - 1 \right) + \frac{A^* p_i}{\mu_i} + \frac{1}{\lambda p_i} \right) \right) \quad (7)$$

3.2 WIP cost with unit completion time

In this case, the completion time of each unit should be calculated. This case is more complicated than the other one due to considering working days. To handle this problem first of all, the total number of items remanufactured in each day (S_i) should be calculated. As each day is considered as one shift or 8 working hours and considering equation (4) as the time required for inspection and remanufacturing the *jth* item, the total number of products to complete within 8 hours is the largest integer satisfying the following inequality. Note that, the left hand side of the inequality is the total required time to remanufacture S_i number of items.

$$\frac{1}{\lambda p_i} + \frac{S_i}{\mu_i} \le 8 \quad (8)$$

Thus, S_i can be calculated by equation (9):

$$S_i = \left\lfloor \mu_i \left(8 - \frac{1}{\lambda p_i} \right) \right\rfloor \quad (9)$$

On the other hand, considering equation (4), the total waiting time for the first set of S_i products is:

$$\sum_{j=1}^{j=S_i} WT_j = \sum_{j=1}^{j=S_i} \left(\frac{1}{\lambda p_i} + \frac{j}{\mu_i} \right) = \frac{S_i}{\lambda p_i} + \frac{S_i (S_i + 1)}{2\mu_i} \quad (10)$$

Similarly, the total waiting time for the second set of S_i products would be:

$$\sum_{j=S_i+1}^{j=2S_i} WT_j = \sum_{j=S_i+1}^{j=2S_i}\left(16+\frac{1}{\lambda p_i}+\frac{j}{\mu_i}\right)=16S_i+\frac{S_i}{\lambda p_i}+\frac{3S_i^{\,2}+S_i}{2\mu_i} \tag{11}$$

Regarding equations (10) and (11), the total waiting time for the products remanufactured in the k^{th} day is:

$$\sum_{j=(k-1)S_i+1}^{j=kS_i} WT_j = \sum_{j=(k-1)S_i+1}^{j=kS_i}\left(16(k-1)+\frac{1}{\lambda p_i}+\frac{j}{\mu_i}\right)=16S_i(k-1)+\frac{S_i}{\lambda p_i}+\frac{(2k-1)S_i^{\,2}+S_i}{2\mu_i} \tag{12}$$

Knowing this fact that for all of the required days, except the last one, at least S_i products would be remanufactured, it is concluded that equation (12) is true for working days from 1 to R_i-1. Hence, the total waiting time for the products remanufactured during day 1 to R_i-1 can be obtained by solving equation (13):

$$\sum_{k=1}^{k=R_i-1}\left(16S_i(k-1)+\frac{S_i}{\lambda p_i}+\frac{(2k-1)S_i^{\,2}+S_i}{2\mu_i}\right)=\frac{16S_i(R_i-1)(R_i-2)}{2}+\frac{S_i(R_i-1)}{\lambda p_i}+\frac{S_i^{\,2}(R_i-1)^2+S_i(R_i-1)}{2\mu_i} \tag{13}$$

For the products remaining till the last day to remanufacture, total waiting time is:

$$\sum_{j=(R_i-1)S_i+1}^{j=A^*p_i} WT_j = \sum_{j=(R_i-1)S_i+1}^{j=A^*p_i}\left(16(k-1)+\frac{1}{\lambda p_i}+\frac{j}{\mu_i}\right)=16(R_i-1)(A^*p_i-S_i(R_i-1)) + \frac{A^*p_i-(R_i-1)S_i}{\lambda p_i}+\frac{A^*p_i(A^*p_i+1)}{2\mu_i}-\frac{S_i(R_i-1)\big((R_i-1)S_i-1\big)}{2\mu_i} \tag{14}$$

Total waiting time for the products being remanufactured would be the summation of (13) and (14):

$$\sum_{i\in I} TWT_i = \sum_{i\in I}\ 16(R_i-1)(A^*p_i-S_i(R_i-1))+\frac{A^*p_i-(R_i-1)S_i}{\lambda p_i}+\frac{A^*p_i(A^*p_i+1)}{2\mu_i} -\frac{S_i(R_i-1)\big((R_i-1)S_i-1\big)}{2\mu_i}+\frac{16S_i(R_i-1)(R_i-2)}{2}+\frac{S_i(R_i-1)}{\lambda p_i}+\frac{S_i^{\,2}(R_i-1)^2+S_i(R_i-1)}{2\mu_i} \tag{15}$$

The revised objective function is to maximize:

$$\sum_{i\in I}(A^*p_i(pr_i-c_i)-pr_i(A^*p_i-D_i)\varepsilon)-\alpha\sum_{i\in I}\Big(16(R_i-1)(A^*p_i-S_i(R_i-1)) +\frac{A^*p_i-(R_i-1)S_i}{\lambda p_i}+\frac{A^*p_i(A^*p_i+1)}{2\mu_i}-\frac{S_i(R_i-1)\big((R_i-1)S_i-1\big)}{2\mu_i} +\frac{16S_i(R_i-1)(R_i-2)}{2}+\frac{S_i(R_i-1)}{\lambda p_i}+\frac{S_i^{\,2}(R_i-1)^2+S_i(R_i-1)}{2\mu_i}\Big) \tag{16}$$

Where S_i and R_i are the values introduced in equations (9) and (5), respectively. In the next section, the impact of process rates on the total profit is investigated.

4. Sensitivity analysis

In this section, the impact of remanufacturing rates on the objective function is investigated. The model in which the makespan is considered is referred to as model 1 and the other one as model 2 for the remaining of this paper.

In this numerical experiment, three categories are assumed with processing rates, remanufacturing costs and selling prices such that $\mu_2 < \mu_1 < \mu_3$, $c_1 < c_2 < c_3$ and $pr_1 > pr_2 > pr_3$, respectively. In this case, although remanufacturing cost of the second category is less than the third one and its selling price is higher than selling price for the third category, it possesses lower processing rate leading to produce higher holding cost. Category 1 is preferable to category 2 due to having lower remanufacturing cost, higher selling price and higher processing rate. Thus, under these assumptions, achieving the optimality is not a straight forward action and requires solving the model. The addressed experimental test is implemented on both model 1 and 2.

The results are reported for models 1 and 2 in Figures 3 and 4, respectively. Each graph shows the effect of increasing and decreasing the remanufacturing rate by one. As illustrated in Figure 4, if μ_1 is increased by one, a small improvement happens whereas decreasing it by one deteriorates the objective function slightly. These changes are slight for μ_3, but significantly high for μ_2. Exactly, the same changes can be traced for the second model in Figure 5.

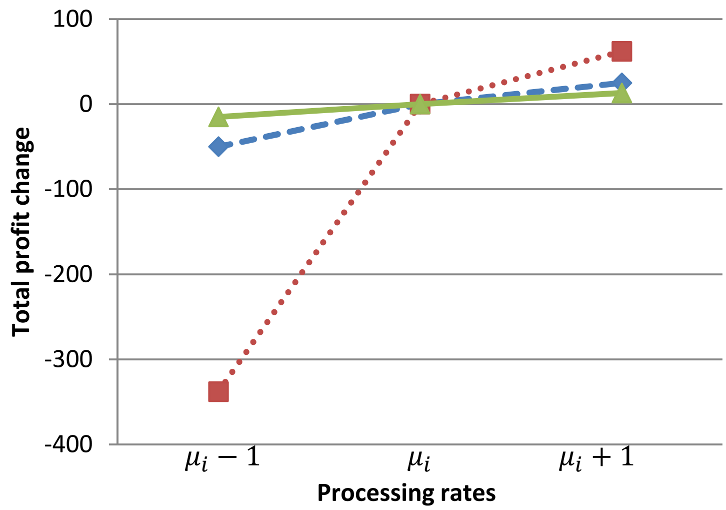

Figure 3: Effect of processing rate changes on the objective function, Solid line: μ_3, Dashed line: μ_1, Dotted line: μ_2

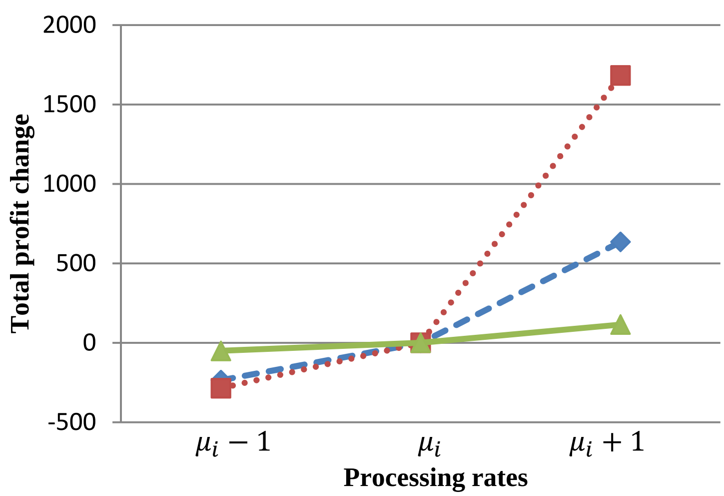

Figure 4: Effect of processing rate changes on the objective function, Solid line: μ_3, Dashed line: μ_1, Dotted line line: μ_2

According to these figures, although the size of change for all of the processing rates was equal, the impact of the largest processing rate is more than the others. Although the amount of time increase/decrease is lower for the second process than the others, a larger change happened in the objective function. Note that although the processes are in parallel, the largest process time still acts like the bottleneck.

On the other hand, the impact of inspection rate should be examined on the objective function. Results are depicted in Figure 5. Since there was no significant impact on the objective function of model 1, it is not included in this illustration. Note that, these mathematical models are created on the basis of the assumption that inspection rate is higher than processing rates.

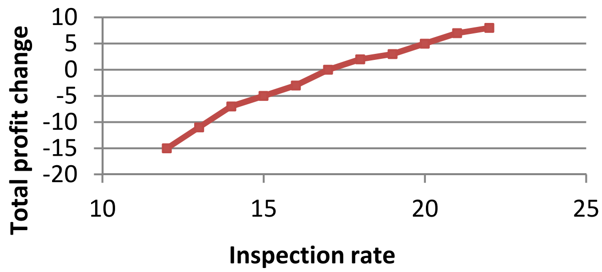

Figure 5: Impact of inspection rate on the total profit

According to Figure 5, inspection rate has a small effect on the objective function which can be ignored. However, increasing inspection rate increases the objective function, as expected.

5. Summary and conclusion

In this paper, the optimal quantity of acquired products is determined for a simple remanufacturing line, considering holding costs for work in process and finished products with a new approach. To calculate holding costs, only the effective time spent by a product in a system is considered. Either shipping/selling the remanufactured products one by one or in batches, holding cost affects total profit as the objective function. For both cases, MINLP models are presented.

It is concluded that, the largest impact of remanufacturing rates on the objective function belongs to the process with the lowest processing rate. If companies seek for higher profit, they should concentrate mostly on the processes with higher process time.

This work can be extended by considering more than 2 stations. In this case, the finish time of each product would be more complicated to calculate. In addition, relaxing the assumption regarding size of inspection rate and process rates, modeling would be a more sophisticated task.

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